

Higgs and Sparticle Spectroscopy with Gauge-Yukawa Unification

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Abstract

We explore the Higgs and sparticle spectroscopy of supersymmetric $SU(4)_c \times SU(2)_L \times SU(2)_R$ models in which the three MSSM gauge couplings and third family (t - b - τ) Yukawa couplings are all unified at M_{GUT} . This class of models can be obtained via compactification of a higher dimensional theory. Allowing for opposite sign gaugino masses and varying m_t within 1σ of its current central value yields a variety of gauge-Yukawa unification as well as WMAP compatible neutralino dark matter solutions. They include mixed bino-Higgsino dark matter, stau and gluino coannihilation scenarios, and the A-resonance solution.

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1 Introduction

Supersymmetric (SUSY) $SO(10)$ GUT (grand unified theory), in contrast to its non-SUSY version, yields third family (t - b - τ) Yukawa unification via the unique renormalizable Yukawa coupling $16 \cdot 16 \cdot 10$, where the 10-plet is assumed to contain the two minimal supersymmetric standard model (MSSM) Higgs doublets H_u and H_d , and the 16-plet contains the 15 chiral fermions per family of the standard model (SM) as well as the right handed neutrino. The implications of this unification have been extensively explored over the years [1, 2]. More recently, it has been argued in [3, 4] that $SO(10)$ Yukawa unification predicts relatively light (\lesssim TeV) gluinos, which can be readily tested [5] at the Large Hadron Collider (LHC). The squarks and sleptons turn out to have masses in the multi-TeV range. Moreover, it is argued in [3, 4] that the lightest neutralino is not a viable cold dark matter candidate, at least in the simplest models of $SO(10)$ Yukawa unification.

Spurred by these developments we have investigated t - b - τ Yukawa unification [4, 6, 7] in the framework of supersymmetric $SU(4)_c \times SU(2)_L \times SU(2)_R$ [8] (4-2-2,

for short). The 4-2-2 structure allows us to consider non-universal gaugino masses while retaining Yukawa unification. An important conclusion reached in [4, 6] is that with same sign non-universal gaugino soft terms, Yukawa unification in 4-2-2 is compatible with neutralino dark matter, with gluino co-annihilation [4, 6, 9, 10] playing an important role. By considering opposite sign gauginos with $\mu < 0$, $M_2 < 0$, $M_3 > 0$ (where μ is the bilinear Higgs mixing term, and M_2 and M_3 are the soft supersymmetry breaking gaugino mass terms corresponding respectively to $SU(2)_L$ and $SU(3)_c$) in [7] we have shown that Yukawa coupling unification consistent with known experimental constraints is realized in 4-2-2. With $\mu < 0$ and opposite sign gauginos, Yukawa coupling unification is achieved for $m_0 \gtrsim 300$ GeV, as opposed to $m_0 \gtrsim 8$ TeV for the case of same sign gauginos, by taming the finite corrections to the b-quark mass. By considering gauginos with $M_2 < 0$ and $M_3 > 0$ and $\mu < 0$, we can obtain the correct sign for the desired contribution to $(g - 2)_\mu$ [11]. This enables us to simultaneously satisfy the requirements of t - b - τ Yukawa unification, neutralino dark matter and $(g - 2)_\mu$, as well as a variety of other known bounds.

Encouraged by the abundance of solutions and coannihilation channels available in the case of Yukawa unified 4-2-2, it is natural to try to further constrain this model. One possible way is to impose unification of t - b - τ Yukawa couplings with the MSSM gauge couplings at M_{GUT} . This is partially inspired from the observation that at M_{GUT} , the unified gauge coupling for the MSSM with TeV scale supersymmetry is ~ 0.7 , while the corresponding third generation Yukawa couplings are of order 0.6. This suggests that the origin of Yukawa couplings and gauge interaction may be closely related, and indeed higher dimensional supersymmetric models have been constructed that predict gauge-Yukawa unification (GYU) [12, 13, 14]. We will briefly summarize one such model later in the paper. The phenomenology of this idea was studied in [14], where it was shown how a suitable choice of low scale SUSY threshold corrections can yield GYU condition in principle, without precisely specifying the origin and values for the soft SUSY breaking parameters.

The main purpose of this paper is to extend the 4-2-2 discussion to the case of GYU in the framework of gravity mediated SUSY breaking scenario. In Section 2 we briefly describe the Yukawa unified 4-2-2 model and the boundary conditions for the soft supersymmetry breaking (SSB) parameters employed in our scan. In Section 3 we summarize the scanning procedure and the various experimental constraints that we impose. In Section 4 we discuss threshold corrections to the Yukawa couplings and summarize from previous studies the findings pertaining to Yukawa unification. We also present new results in this section for Yukawa unification for the case of $\mu > 0$, $M_2 > 0$, $M_3 < 0$ in this section. In Section 5 we discuss GYU with MSSM as the low energy theory. We first describe a concrete model that breaks to SUSY 4-2-2 at M_{GUT} and yields gauge- t - b - τ Yukawa unification condition. We then proceed to discuss the role played by threshold corrections to δy_t in order to obtain GYU. The

important role of the top quark mass in implementing GYU is also emphasized. In Section 6 we present our results and highlight some of the predictions of the GYU 4-2-2 model. The correlation between direct and indirect detection of dark matter and the gauge-Yukawa unification condition is presented in Section 7 where we also display some benchmark points. Our conclusions are summarized in Section 8.

2 The 4-2-2 model

In 4-2-2 the 16-plet of $SO(10)$ matter fields consists of ψ (4, 2, 1) and ψ_c ($\bar{4}$, 1, 2). The third family Yukawa coupling $\psi_c \psi H$, where $H(1, 2, 2)$ denotes the bi-doublet (1,2,2), yields the following relation valid at M_{GUT} ,

$$Y_t = Y_b = Y_\tau = Y_{\nu_\tau}. \quad (1)$$

In a realistic scenario we can expect corrections to Eq.(1) arising, say, from higher dimensional operators. We will assume that these are sufficiently small so that Eq.(1) is valid within a few percent or so.

Supplementing 4-2-2 with a discrete left-right (LR) symmetry [8, 15] (more precisely C-parity) [16] reduces the number of independent gauge couplings in 4-2-2 from three to two. This is because C-parity imposes the gauge coupling unification condition ($g_L = g_R$) at M_{GUT} . We will assume that due to C-parity the SSB mass terms, induced at M_{GUT} through gravity mediated supersymmetry breaking [17] are equal in magnitude for the squarks and sleptons of the three families. The tree level asymptotic MSSM gaugino SSB masses, on the other hand, can be non-universal from the following consideration. From C-parity, we can expect that the gaugino masses at M_{GUT} associated with $SU(2)_L$ and $SU(2)_R$ are the same ($M_2 \equiv M_2^R = M_2^L$). However, the asymptotic $SU(4)_c$ and consequently $SU(3)_c$ gaugino SSB masses can be different. With the hypercharge generator in 4-2-2 given by $Y = \sqrt{2/5} (B - L) + \sqrt{3/5} I_{3R}$, where $B - L$ and I_{3R} are the diagonal generators of $SU(4)_c$ and $SU(2)_R$, we have the following asymptotic relation between the three MSSM gaugino SSB masses:

$$M_1 = \frac{3}{5} M_2 + \frac{2}{5} M_3. \quad (2)$$

The supersymmetric 4-2-2 model with C-parity thus has two independent parameters (M_2 and M_3) in the gaugino sector. In order to implement Yukawa unification it turns out that the SSB Higgs mass terms must be non-universal at M_{GUT} . Namely, $m_{H_u}^2 < m_{H_d}^2$ at M_{GUT} , where m_{H_u} (m_{H_d}) is the up (down) type SSB Higgs mass term. Phenomenological studies of the MSSM typically resort to ‘just-so’ splitting (see Blazek, Dermisek and Raby in [2]) for the MSSM Higgs doublets, while remarking in passing that such a splitting may arise, for example, from D terms. D terms,

however, induce splitting in the squarks and sleptons as well. It is possible to imagine a simple mechanism to implement just-so Higgs SSB mass splitting in either the 4-2-2 or $SO(10)$ models.

We need Higgs fields other than $H(1, 2, 2)$ in order to complete the model. For instance, $\Phi(4, 1, 2) + \bar{\Phi}(\bar{4}, 2, 1)$ field may be used to break 4-2-2 to the SM gauge group. In the 4-2-2 model, just-so Higgs splitting may be understood by writing an $SU(2)_R$ violating bilinear term between the up and down type Higgs doublets. This may be done, for instance, by considering a super-heavy Higgs Δ that transforms as $(1, 1, 3)$ under 4-2-2. If the MSSM doublet comes from $H(1, 2, 2)$ under 4-2-2, the superpotential will have the interaction $HH\Delta$. We may consider the SSB trilinear term $A_\Delta HH\Delta$ and assume that Δ has a non-zero VEV, $\langle\Delta\rangle = Vdiag(1, -1)$ with $V \approx (O)$ TeV. We can thus achieve the desired splitting in the MSSM Higgs doublets. Likewise, we can explain just-so Higgs splitting in $SO(10)$ by using the 45-dimensional Higgs since it contains the $\Delta(1, 1, 3)$ of 4-2-2. We may consider the non-renormalizable coupling $10 \cdot 10 \cdot 45^2$ ($10 \cdot 10 \cdot 45$ is not allowed as 45 is a two-index anti-symmetric representation) in the superpotential, where the 10 is the 10-dimensional representation that has the MSSM Higgs doublets. We may get just-so Higgs splitting by writing the corresponding SSB term with a suitable choice of Yukawa coupling or VEV for the 45.

The fundamental parameters of the 4-2-2 model that we consider are as follows:

$$m_0, m_{H_u}, m_{H_d}, M_2, M_3, A_0, \tan \beta, \text{sign}(\mu). \quad (3)$$

Here m_0 is the universal SSB mass for MSSM sfermions, A_0 is the universal SSB trilinear scalar interaction (with the corresponding Yukawa coupling factored out), $\tan \beta$ is the ratio of the vacuum expectation values (VEVs) of the two MSSM Higgs doublets, and the magnitude of μ , but not its sign, is determined by the radiative electroweak breaking (REWSB) condition. Although not required, we will assume that the gauge coupling unification condition $g_3 = g_1 = g_2$ holds at M_{GUT} in 4-2-2. Such a scenario can arise, for example, from a higher dimensional $SO(10)$ [18] or $SU(8)$ [12] model after suitable compactification.

3 Phenomenological constraints and scanning procedure

We employ the ISAJET 7.80 package [19] to perform random scans over the parameter space listed in Eq.(3). In this package, the weak scale values of gauge and third generation Yukawa couplings are evolved to M_{GUT} via the MSSM renormalization group equations (RGEs) in the \overline{DR} regularization scheme. We do not strictly enforce

the unification condition $g_3 = g_1 = g_2$ at M_{GUT} , since a few percent deviation from unification can be assigned to unknown GUT-scale threshold corrections [20]. The difference between $g_1(=g_2)$ and g_3 at M_{GUT} is no worse than 4%. If neutrinos acquire mass via Type I seesaw, the impact of the neutrino Dirac Yukawa coupling on the RGEs of the SSB terms, gauge couplings and the third generation Yukawa couplings is significant only for relatively large values (~ 2 or so). In the GYU 4-2-2 model we expect the largest (third family) Dirac Yukawa coupling to be comparable to the gauge couplings (~ 0.6 at M_{GUT}). Therefore, we do not include the Dirac neutrino Yukawa coupling in the RGEs.

The various boundary conditions are imposed at M_{GUT} and all the SSB parameters, along with the gauge and Yukawa couplings, are evolved back to the weak scale M_Z . In the evaluation of Yukawa couplings the SUSY threshold corrections [21] are taken into account at the common scale $M_{\text{SUSY}} = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$. The entire parameter set is iteratively run between M_Z and M_{GUT} using the full 2-loop RGEs until a stable solution is obtained. To better account for leading-log corrections, one-loop step-beta functions are adopted for gauge and Yukawa couplings, and the SSB parameters m_i are extracted from RGEs at multiple scales $m_i = m_i(m_i)$. The RGE-improved 1-loop effective potential is minimized at an optimized scale M_{SUSY} , which effectively accounts for the leading 2-loop corrections. Full 1-loop radiative corrections are incorporated for all sparticle masses.

The requirement of REWSB [22] puts an important theoretical constraint on the parameter space. Another important constraint comes from limits on the cosmological abundance of stable charged particles [23]. This excludes regions in the parameter space where charged SUSY particles, such as $\tilde{\tau}_1$ or \tilde{t}_1 , become the lightest supersymmetric particle (LSP). We accept only those solutions for which one of the neutralinos is the LSP and saturates the WMAP (Wilkinson Microwave Anisotropy Probe) dark matter relic abundance bound.

We have performed random scans for the following parameter range:

$$\begin{aligned}
0 &\leq m_0, m_{H_u}, m_{H_d} \leq 20 \text{ TeV} \\
-2 \text{ TeV} &\leq M_2 \leq 2 \text{ TeV} \\
-2 \text{ TeV} &\leq M_3 \leq 2 \text{ TeV} \\
45 &\leq \tan \beta \leq 55 \\
-3 &\leq A_0/m_0 \leq 3 \\
\mu &< 0, \mu > 0
\end{aligned} \tag{4}$$

where $m_t = 173.3 \pm 1.1 \text{ GeV}$ [24] is the top quark pole mass. The value of the top quark mass is very crucial, as we shall see later, for GYU. We use $m_b(m_Z) = 2.83 \text{ GeV}$ which is hard-coded into ISAJET. The above choice of parameters is influenced by our previous experience with the 4-2-2 model.

In scanning the parameter space, we employ the Metropolis-Hastings algorithm as described in [25]. All of the collected data points satisfy the requirement of REWSB, with the neutralino in each case being the LSP. We direct the Metropolis-Hastings algorithm to search for solutions with GYU. After collecting the data, we impose the mass bounds on all the particles [23] and use the IsaTools package [26] to implement the following phenomenological constraints on points that have GYU to within 20%:

$$\begin{aligned}
m_h \text{ (lightest Higgs mass)} &\geq 114.4 \text{ GeV} & [27] \\
BR(B_s \rightarrow \mu^+ \mu^-) &< 5.8 \times 10^{-8} & [28] \\
2.85 \times 10^{-4} \leq BR(b \rightarrow s \gamma) &\leq 4.24 \times 10^{-4} \text{ (} 2\sigma \text{)} & [29] \\
0.15 \leq \frac{BR(B_u \rightarrow \tau \nu_\tau)_{\text{MSSM}}}{BR(B_u \rightarrow \tau \nu_\tau)_{\text{SM}}} &\leq 2.41 \text{ (} 3\sigma \text{)} & [29] \\
\Omega_{\text{CDM}} h^2 &= 0.111^{+0.028}_{-0.037} \text{ (} 5\sigma \text{)} & [30] \\
0 \leq \Delta(g-2)_\mu/2 &\leq 55.6 \times 10^{-10} & [11]
\end{aligned}$$

In the case of $\Delta(g-2)_\mu$, we only require that the GYU 4-2-2 model does no worse than the SM. However, we do give examples of solutions that satisfy the $\Delta(g-2)_\mu/2$ constraint to within 3σ .

4 Threshold corrections and Yukawa unification

The SUSY threshold corrections to the top, bottom and tau Yukawa couplings play a crucial role in t - b - τ Yukawa coupling unification. In general, the bottom Yukawa coupling y_b can receive large threshold corrections, while the threshold corrections to y_t are typically smaller [21]. The scale at which Yukawa coupling unification occurs is set equal to M_{GUT} , the scale of gauge coupling unification. Consider first the case $y_t(M_{\text{GUT}}) \approx y_\tau(M_{\text{GUT}})$. The SUSY correction to the tau lepton mass is given by $\delta m_\tau = v \cos \beta \delta y_\tau$. For the large $\tan \beta$ values of interest here, there is sufficient freedom in the choice of δy_τ to achieve $y_t \approx y_\tau$ at M_{GUT} . This freedom stems from the fact that $\cos \beta \simeq 1/\tan \beta$ for large $\tan \beta$, and so we may choose an appropriate δy_τ and $\tan \beta$ to give us both the correct τ lepton mass and $y_t \approx y_\tau$. The SUSY contribution to δy_b has to be carefully monitored in order to achieve Yukawa coupling unification $y_t(M_{\text{GUT}}) \approx y_b(M_{\text{GUT}}) \approx y_\tau(M_{\text{GUT}})$.

We choose the sign of δy_i ($i = t, b, \tau$) from the perspective of evolving y_i from M_{GUT} to M_Z . With this choice, δy_b must receive a negative contribution ($-0.27 \lesssim \delta y_b/y_b \lesssim -0.15$) in order to realize Yukawa coupling unification [7]. This is a narrow interval considering the full range of $-0.4 \lesssim \delta y_b/y_b \lesssim 0.6$ that we found in the data that we collected. The dominant contribution to δy_b comes from the finite corrections of the gluino and chargino loops, and in our sign convention, is approximately given by [21]

$$\delta y_b^{\text{finite}} \approx \frac{g_3^2}{12\pi^2} \frac{\mu m_{\tilde{g}} \tan \beta}{m_{\tilde{b}}^2} + \frac{y_t^2}{32\pi^2} \frac{\mu A_t \tan \beta}{m_{\tilde{t}}^2}, \quad (5)$$

where g_3 is the strong gauge coupling, $m_{\tilde{g}}$ is the gluino mass, $m_{\tilde{b}}$ and $m_{\tilde{t}}$ are the lighter sbottom and stop masses, and A_t is the top trilinear (scalar) coupling.

The logarithmic corrections to y_b are positive, which leaves the finite corrections to provide for the correct overall negative δy_b in order to realize Yukawa unification. The gluino contribution (Eq.(5)) is positive for $\mu > 0$ and same sign gaugino soft mass terms. Thus, the chargino contribution (Eq.(5)) must play an essential role to provide the required negative contribution to δy_b . This can be achieved with suitably large values of both m_0 and A_t . This large value of m_0 and A_t is the reason behind the requirement of $m_0 \gtrsim 6 \text{ TeV}$ and $A_0/m_0 \sim -2.6$ in the $SO(10)$ model discussed in [3]. The parameter $\tan \beta$ also lies in a narrow range $48 \lesssim \tan \beta \lesssim 52$. A similar trend was shown in [4] for the 4-2-2 model with same sign gauginos and $\mu > 0$. The latter model displays Yukawa coupling unification consistent with WMAP data via bino-gluino coannihilation.

In an $SO(10)$ -like [3] model with same sign gauginos, the case $\mu < 0$ is not favored because of the negative contribution to $\Delta(g-2)_\mu \propto \mu M_2$ which, instead, needs to be positive. Therefore, while the Yukawa unified $SO(10)$ and 4-2-2 [4] (with $\mu, M_2, M_3 > 0$) models do not provide the required contribution to $\Delta(g-2)_\mu$ because of heavy particles, they do no worse than the SM in this respect.

One can improve the situation immensely by considering the case of opposite sign gaugino soft terms which is allowed by the 4-2-2 model. We showed in [7] the parameter space corresponding to $\mu, M_2 < 0, M_3 > 0$ that gives Yukawa coupling unification with a sub-TeV sparticle spectrum which is consistent with all known experimental bounds including $\Delta(g-2)_\mu$. Another possibility is to consider $\mu, M_2 > 0, M_3 < 0$ (the parameter space for this case has not been previously discussed in the literature). This becomes possible because the gluino contribution to δy_b is of the correct (negative) sign.

In order to quantify Yukawa coupling unification, following [3], we define the quantity R as,

$$R = \frac{\max(y_t, y_b, y_\tau)}{\min(y_t, y_b, y_\tau)} \quad (6)$$

Thus, R is a useful indicator for Yukawa unification with $R \lesssim 1.1$, for instance, corresponding to Yukawa unification to within 10%, while $R = 1.0$ denotes ‘perfect’ Yukawa unification.

In Figure 1 we show a comparison between the four model types considered, *i.e.* the $SO(10)$ model and 4-2-2 models with $\{\mu > 0, M_2 > 0, M_3 > 0\}$, $\{\mu < 0, M_2 <$

$0, M_3 > 0\}$ and $\{\mu > 0, M_2 > 0, M_3 < 0\}$. We show plots in the $m_0 - A_0/m_0$ plane for these models. Gray points are consistent with REWSB and $\tilde{\chi}_1^0$ LSP. Orange, light blue and purple points are subsets of gray points with $R \lesssim 1.2, 1.1, 1.02$ respectively. As previously explained, in the $SO(10)$ and 4-2-2 models with $\mu > 0$ and same sign gauginos, Yukawa coupling unification can only be achieved for large values of m_0 . Also, the value of A_0/m_0 is very restricted. On the other hand, with opposite sign gauginos one can realize very credible Yukawa unification with relatively small m_0 values. Also as previously described, since the gluino loop provides the required δy_b , A_0/m_0 is no longer restricted by Yukawa coupling unification and can vary over a very wide range.

In Figure 2 we display an interesting difference between the same sign and opposite

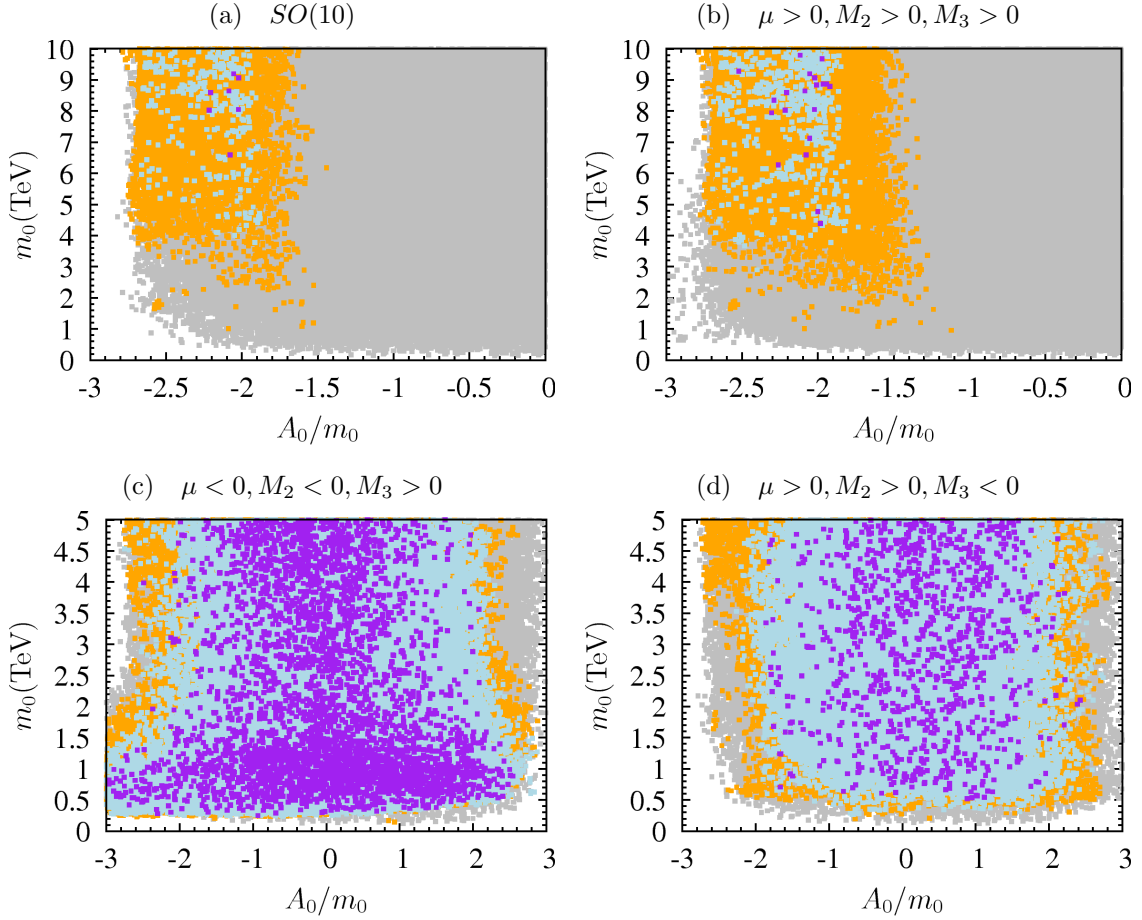


Figure 1: Plots in the $m_0 - A_0/m_0$ plane for the $SO(10)$ model and three classes of 4-2-2 models. Gray points are consistent with REWSB and $\tilde{\chi}_1^0$ LSP. Orange, light blue and purple points are subsets of gray points with $R \lesssim 1.2, 1.1, 1.02$ respectively.

sign gaugino cases in the $|M_3| - m_0$ plane. Shown in gray are points that satisfy the requirements of REWSB and $\tilde{\chi}_1^0$ LSP. In green, blue and orange, we show points that further satisfy Yukawa unification to within 20%, 15% and 10% respectively. Red points satisfy the particle mass bounds in addition to having $R \lesssim 1.1$. The trend of a lower M_3 in the case of same sign gauginos is very apparent if we require Yukawa coupling unification. The reason for this is again that we need to suppress the finite correction to the bottom quark mass coming from the gluino loop (see Eq.(5)). The case of opposite sign gauginos, in stark contrast, shows that essentially any value of $|M_3|$ is acceptable as far as Yukawa coupling unification is concerned. The orange region in the bottom left in this case is excluded because of the lower bound on the gluino mass. It is also instructive to consider the $m_{\tilde{g}} - A_t$ plane in the case of same sign gauginos shown in Figure 3. In this figure, $m_{\tilde{g}}$ is the physical gluino mass and A_t is the value of the top trilinear (scalar) coupling at the scale $Q = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$. The color coding is the same as in Figure 2. This figure shows that a lighter gluino is required for Yukawa coupling unification with a smaller absolute value of A_t . This again reflects the fact that for Yukawa coupling unification, we need to suppress the gluino contribution to δy_b in favor of the chargino contribution.

Finally, it is interesting to note that with opposite sign gauginos, the MSSM parameter $\tan \beta$ varies over a wider range, $44 \lesssim \tan \beta \lesssim 54$. With same sign gauginos, on the other hand, $48 \lesssim \tan \beta \lesssim 52$. Among other interesting features of a Yukawa unified model with opposite sign gauginos is the presence of various channels for

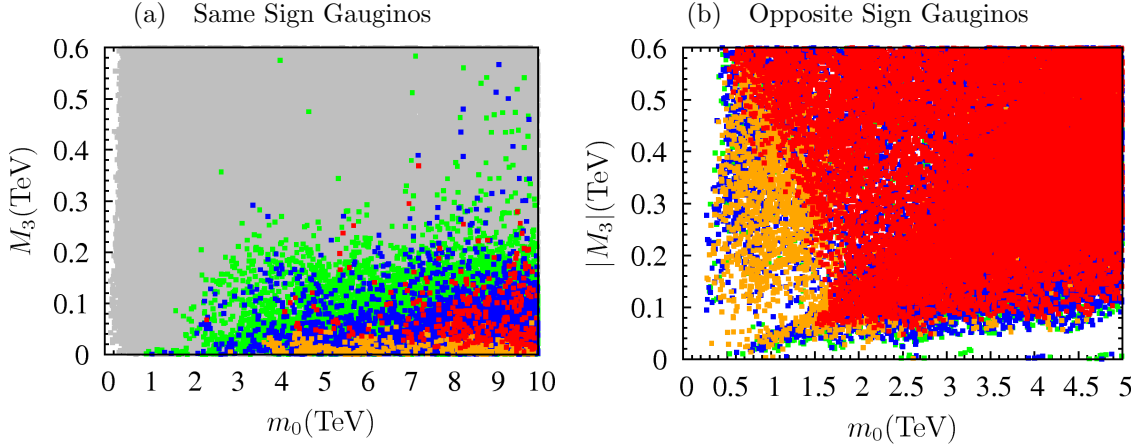


Figure 2: Plots in the $|M_3| - m_0$ plane for same sign (left) and opposite sign (right) gaugino (including points for both $\{\mu < 0, M_2 < 0, M_3 > 0\}$ and $\{\mu > 0, M_2 > 0, M_3 < 0\}$) cases. Gray points are consistent with REWSB and $\tilde{\chi}_1^0$ LSP. Green, blue and orange points are subsets of gray points with $R \lesssim 1.2, 1.15, 1.1$ respectively. Red points satisfy particle mass bounds in addition to $R \lesssim 1.1$.

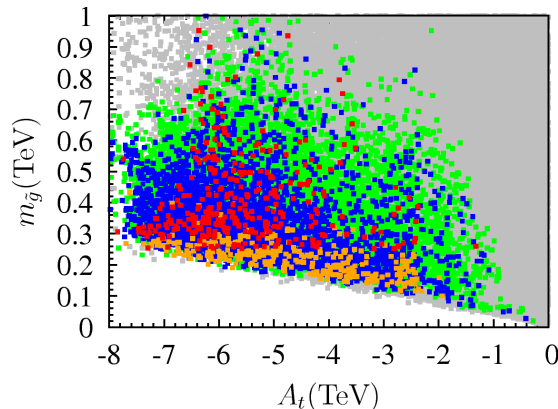


Figure 3: Plot in the $m_{\tilde{g}} - A_t$ plane for same sign gauginos. Color coding same as in Figure 2.

realizing the desired $\tilde{\chi}_1^0$ relic density. In particular, in [7] we showed the existence of stau coannihilation, bino-wino coannihilation, gluino coannihilation and CP-odd Higgs resonance solutions for the case ($\mu < 0, M_2 < 0, M_3 > 0$). In contrast, for the Yukawa unified $SO(10)$ model, only the light Higgs resonance solution is consistent with the WMAP relic density. It is interesting to note that in the case of 4-2-2 models (with $\mu > 0, M_2 > 0, M_3 > 0$), it is not possible to get the well-known stau ($\tilde{\tau}$) coannihilation channel. This is because in the $\tilde{\tau}$ mass² matrix the diagonal terms are proportional to m_0^2 , whereas the off-diagonal terms are proportional to $A_\tau m_\tau$, where A_τ is the low-scale value of the tau trilinear (scalar) coupling. For $\mu > 0, M_2 > 0, M_3 > 0$, one needs a heavy m_0 in order to realize Yukawa coupling unification. One therefore needs $A_\tau \sim m_0^2/m_\tau$ in order for the off-diagonal terms to contribute to give a small stau mass $m_{\tilde{\tau}} \sim m_{\tilde{\chi}_1^0}$, where $\tilde{\chi}_1^0$ is the lightest neutralino. This, clearly, is not possible for large m_0 values. The parameter space of the $SO(10)$ model is a subset of the 4-2-2 model with $\{\mu > 0, M_2 > 0, M_3 > 0\}$ and so these remarks apply to $SO(10)$ as well.

5 Gauge-Yukawa unification

In this section, we first describe a specific model where GYU may happen. We then move on to discuss SUSY particle thresholds and their effects on analyzing GYU. It is helpful to define, in analogy with R , a parameter GY that quantifies GYU;

$$GY = \frac{\max(g_1, g_2, g_3, y_t, y_b, y_\tau)}{\min(g_1, g_2, g_3, y_t, y_b, y_\tau)} \quad (7)$$

5.1 Model for Gauge-Yukawa unification

A six dimensional model realizing unification of the gauge couplings (g_1, g_2, g_3) and the third family Yukawa couplings (y_t, y_b, y_τ) was presented in [12]. It has $SU(8)$ gauge symmetry with N=2 SUSY, which corresponds to N=4 SUSY in 4D, and thus only the gauge multiplet can be introduced in the bulk. The 6D N=2 gauge multiplet, expressed in terms of 4D, N=4 gauge multiplet, contains the vector multiplet $V(A_\mu, \lambda)$ and three chiral multiplets in the adjoint (63-dimensional) representation of the gauge group. The 63-dimensional gauge multiplet contains the gauge bosons (and their superpartners), while the three 63-dimensional chiral multiplets contain the third family matter fermions and the Higgs bosons plus their superpartners. The two extra dimensions are compactified on the orbifold T^2/Z_6 , and a suitable choice of the Z_6 transformation matrix breaks $SU(8)$ down to $SU(4) \times SU(2)_L \times SU(2)_R \times U(1)^2$. The theory reduces to 4D N=1 SUSY 4-2-2 model and two additional $U(1)$ factors. The massless modes after compactification are the 4-2-2 gauge fields, $(\mathbf{15}, \mathbf{1}, \mathbf{1}), (\mathbf{1}, \mathbf{3}, \mathbf{1}), (\mathbf{1}, \mathbf{1}, \mathbf{3})$ two singlet vector fields $(\mathbf{1}, \mathbf{1}, \mathbf{1})$ and $(\mathbf{1}, \mathbf{1}, \mathbf{1})$, third-family matter fermions $\Psi_L = (\mathbf{4}, \mathbf{2}, \mathbf{1})_{2,0}$ and $\Psi_{\bar{R}} = (\bar{\mathbf{4}}, \mathbf{1}, \mathbf{2})_{-2,-4}$, and the bi-doublet Higgs fields, $H_1 = (\mathbf{1}, \mathbf{2}, \mathbf{2})_{0,4}$ and $H_2 = (\mathbf{1}, \mathbf{2}, \mathbf{2})_{0,-4}$.

The trilinear coupling for the chiral multiplets

$$S = \int d^6x \left[\int d^2\theta \, 2 \, \text{Tr} \left(-\sqrt{2} g_6 \Sigma [\Phi, \Phi^c] \right) + h.c. \right] \quad (8)$$

includes the third family Yukawa interaction terms

$$S = \int d^6x \int d^2\theta \, y_6 \Psi_L H_1 \Psi_{\bar{R}} + h.c. \quad (9)$$

In Eq. (8), Σ, Φ, Φ^c are chiral multiplets containing the third family chiral fields, Ψ_L and $\Psi_{\bar{R}}$, and the bi-doublet Higgs fields, H_1 and H_2 , and g_6 and y_6 are the 6D gauge and Yukawa couplings. Eqs. (8) and (9) lead to $g_6 = y_6$ with proper renormalization of the kinetic terms. Integrating out the two extra dimensions, we obtain $y_4 = g_4$ for the 4D coupling leading to

$$g_1 = g_2 = g_3 = y_t = y_b = y_\tau (= y_{\nu_\tau}^{\text{Dirac}}) \quad (10)$$

at the compactification scale (M_c) which we identify with the four dimensional unification scale M_{GUT} . We assume that the 4-2-2 symmetry, as well as the two extra $U(1)$ are broken at M_{GUT} to the $SU(3)_c \times SU(2)_L \times U(1)_Y$ using suitable Higgs vevs on the brane. We further assume that the breaking of the two extra $U(1)$ symmetries does not cause D term splittings so that the universality of squark mass² terms at M_{GUT} is preserved. The first and second families are treated as brane fields to cancel the brane localized gauge anomalies. The Yukawa couplings for the first and second

families are suppressed by a large volume factor, but there is no good reason as to why the mass of the first family is hierarchically small. The particle spectrum below M_{GUT} is the same as in MSSM. For related discussions see Ref. [13].

5.2 SUSY thresholds and Gauge-Yukawa unification

As previously mentioned, the bottom quark and tau lepton Yukawa couplings receive larger threshold corrections than y_t . Since the gauge coupling is more or less fixed ~ 0.69 , and since Yukawa coupling unification typically occurs for $y_t \approx y_b \approx y_\tau \sim 0.6$, the quantity $GY \sim 1.15$ for the Yukawa unified models discussed above. If we desire to impose GYU on our models, y_t becomes the bottleneck for a given top mass as typically y_b and y_τ can be made larger than y_t by a suitable choice of the SUSY spectrum. In particular, the values of y_b and y_τ at M_{GUT} can be pushed up to $y_b(M_{\text{GUT}}) \sim 1.2g_{\text{GUT}}$ and $y_\tau(M_{\text{GUT}}) \sim 1.2g_{\text{GUT}}$, where g_{GUT} is the value of the unified gauge coupling at M_{GUT} . The leading SUSY threshold correction to the top quark mass is given by [21]

$$\delta y_t^{\text{finite}} \approx \frac{g_3^2}{12\pi^2} \frac{\mu m_{\tilde{g}} \tan \beta}{m_{\tilde{t}}^2} \quad (11)$$

In our sign convention (evolving the couplings from M_{GUT} to M_Z), a negative contribution to δy_t is preferred. Naively, a larger negative contribution allows for a larger $y_t(M_{\text{GUT}})$. However, in the case of same sign gauginos with $\mu > 0$, we get a positive contribution to δy_t , in which case a large m_0 value is required. The requirement of a large m_0 can be argued from just requiring Yukawa coupling unification. The significance of looking at the sign of the correction to δy_t in this case is the realization that

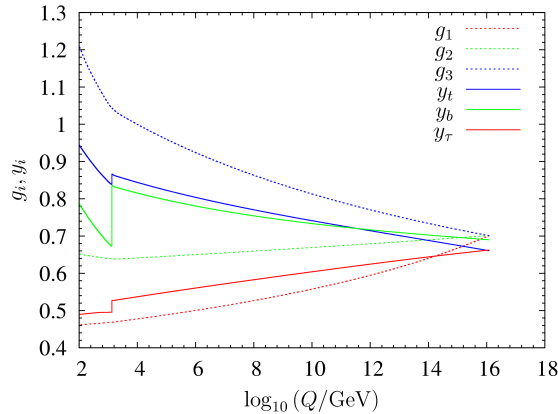


Figure 4: Gauge-Yukawa unification to within 6% in $SU(4)_c \times SU(2)_L \times SU(2)_R$ (4-2-2).

it may not be possible to achieve (more or less) gauge-Yukawa unification at all. We see that $GY \gtrsim 1.13$ in the data that we have collected. In the case of opposite sign gauginos, on the other hand, our choice of the sign of μ gives a negative contribution to δy_t . We should, therefore, expect that GYU is allowed in the case of opposite sign gauginos.

In Figure 4 we show the evolution of the gauge couplings and the third generation Yukawa couplings that unify to within 6% in the 4-2-2 model. The spectrum for this point is given as Point 4 in Table 1.

5.3 Gauge-Yukawa unification and m_t

It is perhaps not too surprising that the parameter GY , a measure of GYU, depends sensitively on the top quark mass m_t . It is, therefore, instructive to study how GYU is affected as one varies m_t . We plot in Figure 5 GY as a function of m_t . As expected, GYU prefers a larger top mass, with near perfect unification possible for $m_t = 177$ GeV. We next discuss GYU allowing for a 1σ variation in the top mass.

6 Gauge-Yukawa unification and sparticle spectroscopy

We present here the results of the scan over the parameter space listed in Eq.(4) after allowing for m_t to vary within 1σ of its central value. In Figure 6 we show results in the $M_3 - M_2$ plane. As previously explained, gauge-Yukawa unification prefers opposite sign gauginos. We emphasize this by only showing the two cases of relative sign gauginos and leaving two quadrants empty in Figure 6. (Same sign gauginos GY

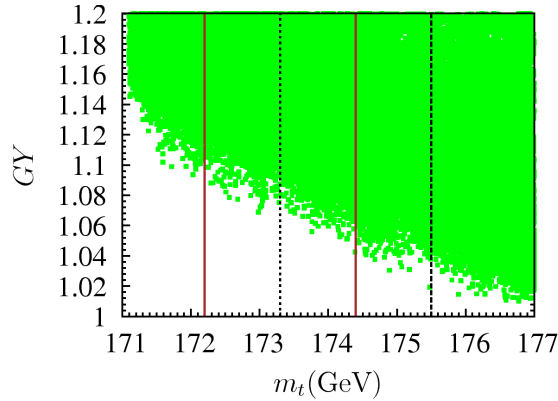


Figure 5: Plot of GY versus m_t . The vertical lines correspond to $m_t = 172.2, 173.3, 174.4$ and 175.5 GeV.

unification of order 10% or higher. See later.) The gray points are consistent with REWSB and $\tilde{\chi}_1^0$ LSP, while the green points also satisfy the particle mass bounds and constraints from $BR(B_s \rightarrow \mu^+\mu^-)$, $BR(b \rightarrow s\gamma)$ and $BR(B_u \rightarrow \tau\nu_\tau)$. In addition, we require that the green points fare no worse than the SM as far as $(g-2)_\mu$ is concerned. The blue points belong to the subset of green points that satisfies the WMAP bounds on $\tilde{\chi}_1^0$ dark matter abundance. Points in red represent the subset of blue points that satisfies gauge-Yukawa coupling unification to within 10%. We also show the lines $M_3 = -6.3M_2$ and $M_3 = -0.12M_2$. The slopes of these lines indicate bino-wino and bino-gluino coannihilation in the $M_3 - M_2$ plane. If we start off with a universal gaugino mass at M_{GUT} , we get $M_2/M_1(Q) \approx \pm 1.89$ and $M_3/M_1(Q) \approx \pm 4.67$, where the negative sign is for the case of opposite sign gauginos. Therefore, in order to get bino-wino coannihilation we should set $M_1/M_2(M_{\text{GUT}}) \approx \pm 1.89$. Substituting this ratio of M_1 and M_2 in Eq. (2) we can infer that bino-wino coannihilation will occur for $M_3 \approx -6.3M_2$. A similar calculation shows that for bino-gluino coannihilation we should set $M_3 \approx -0.12M_2$.

In Figure 7 we show the results in the $GY - m_0$ and $GY - \tan\beta$ planes. There is no visible distinction between the two classes of opposite sign gaugino models in these two planes, which is why we plot the data from the two sets in the same

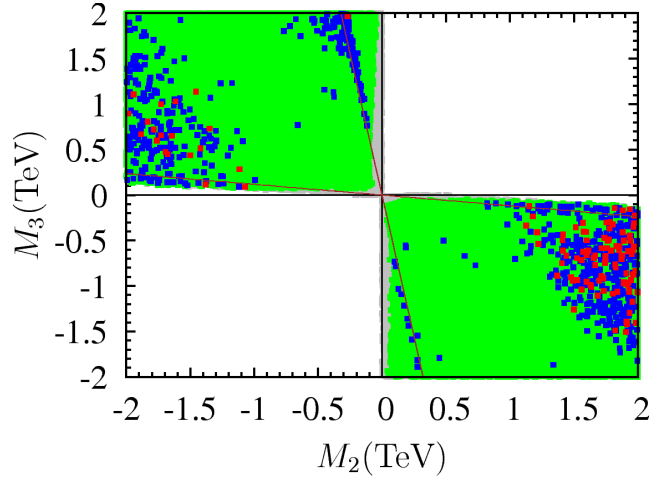


Figure 6: Results in the $M_3 - M_2$ plane. Gray points are consistent with REWSB and $\tilde{\chi}_1^0$ LSP. Green points satisfy particle mass bounds and constraints from $BR(B_s \rightarrow \mu^+\mu^-)$, $BR(b \rightarrow s\gamma)$ and $BR(B_u \rightarrow \tau\nu_\tau)$. In addition, we require that green points do no worse than the SM in terms of $(g-2)_\mu$. Blue points belong to a subset of green points and satisfy the WMAP bounds on $\tilde{\chi}_1^0$ dark matter abundance. Points in red represent the subset of blue points satisfying gauge-Yukawa coupling unification to within 10%. We also show the lines $2M_3 = -13M_2$ and $41M_3 = -6M_2$ discussed in the text.

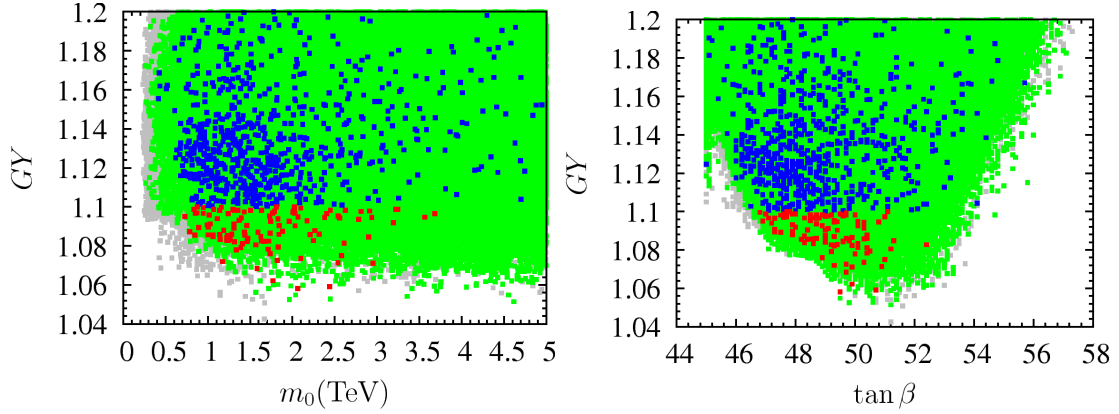


Figure 7: Plots in the $GY - m_0$ and $GY - \tan \beta$ planes. The two classes of opposite sign gaugino models are shown together. Color coding same as in Figure 6.

figure. The color coding is the same as in Figure 6. It can be seen that a relatively large $m_0 (\sim 500 \text{ GeV})$ is required even without imposing any of the experimental constraints. After including the experimental constraints, we are forced to have $m_0 \sim 1.5 \text{ TeV}$. This is to be contrasted with the situation depicted in Figure 1 where $m_0 \sim 300 \text{ GeV}$ suffices for Yukawa coupling unification compatible with all constraints. This may be understood from the fact that keeping all other parameters fixed, a larger m_0 value tends to push up the value of $y_t(M_{\text{GUT}})$ closer to the unified gauge coupling. Likewise, we must have $46 \lesssim \tan \beta \lesssim 54$ with an even narrower range ($47 \lesssim \tan \beta \lesssim 52$) if we consider the experimental constraints. Yukawa coupling

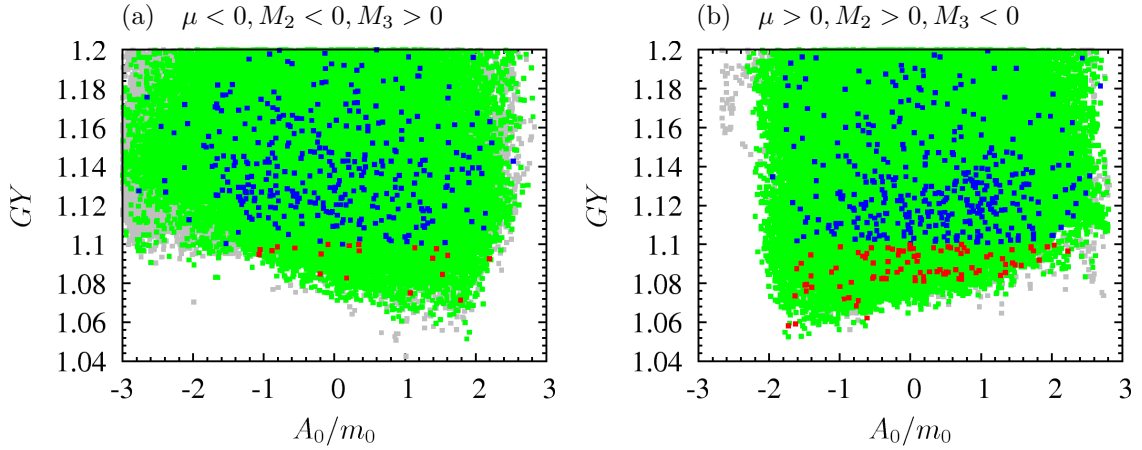


Figure 8: Plots in the $GY - A_0/m_0$ plane for the two classes of opposite sign gaugino models. Color coding same as in Figure 6.

unification, on the other hand, allows for $44 \lesssim \tan \beta \lesssim 54$ for Yukawa unification consistent with experimental constraints.

In Figure 8 we show plots in the $GY - A_0/m_0$ plane for the two classes of opposite sign gaugino models. The color coding is the same as in Figure 6. It is evident that GYU with $\mu > 0$ prefers $A_0/m_0 < 0$, and vice versa. This is different from just Yukawa unified 4-2-2 as seen clearly from Figure 1. This stems from the finite chargino contribution to δy_b which is proportional to μA_t . In the case of Yukawa

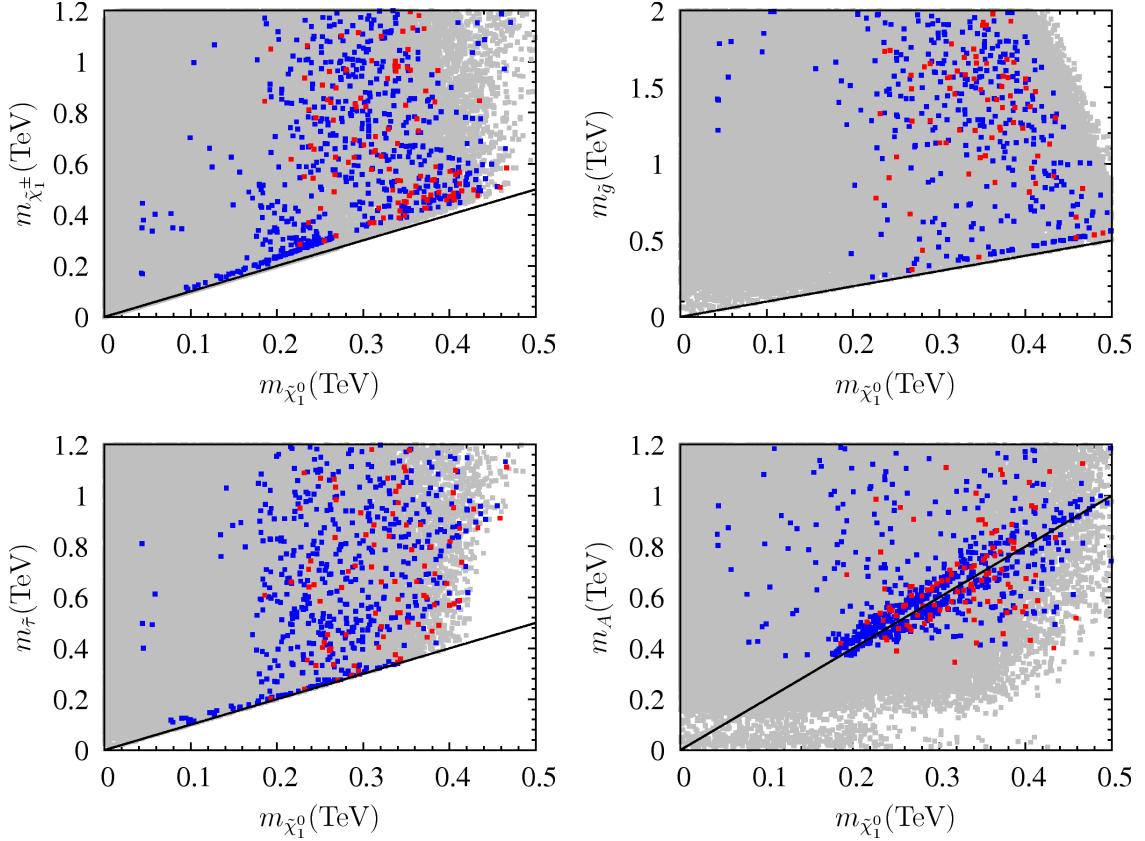


Figure 9: Plots in the $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$, $m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$, $m_{\tilde{\tau}} - m_{\tilde{\chi}_1^0}$ and $m_A - m_{\tilde{\chi}_1^0}$ planes. The gray points satisfy the requirements of REWSB and $\tilde{\chi}_1^0$ LSP. The blue points, in addition, satisfy particle mass bounds and constraints from $BR(B_s \rightarrow \mu^+ \mu^-)$, $BR(B_u \rightarrow \tau \nu_\tau)$ and $BR(b \rightarrow s \gamma)$. In addition, we require that these points do no worse than the SM in terms of the $(g - 2)_\mu$ prediction. The red points correspond to GYU to within 10% in addition to these constraints. We show in the $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$, $m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\tau}} - m_{\tilde{\chi}_1^0}$ planes the unit slope lines that indicate the respective coannihilation channels. In the $m_A - m_{\tilde{\chi}_1^0}$ plane we show the line $m_A = 2m_{\tilde{\chi}_1^0}$ that signifies the A resonance channel.

unification, one can have a small m_0 value for which the chargino contribution is sub-dominant. In GYU on the other hand, m_0 is large as previously explained. This, coupled with the fact that we need the threshold correction to δy_b to be negative, shows that $\mu A_0/m_0 < 0$ is preferred for GYU.

In Figure 9 we show the relic density channels consistent with GYU in the $m_{\tilde{\chi}_1^\pm}$ - $m_{\tilde{\chi}_1^0}$, $m_{\tilde{g}}$ - $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\tau}}$ - $m_{\tilde{\chi}_1^0}$ and m_A - $m_{\tilde{\chi}_1^0}$ planes. The gray points in this figure satisfy the requirements of REWSB and $\tilde{\chi}_1^0$ LSP. The blue points, in addition, satisfy the particle mass bounds and constraints from $BR(B_s \rightarrow \mu^+ \mu^-)$, $BR(B_u \rightarrow \tau \nu_\tau)$ and $BR(b \rightarrow s \gamma)$. In addition, we require that these points do no worse than the SM in terms of the $(g - 2)_\mu$ prediction. The red points correspond to GYU to within 10% in addition to these constraints. We can see in Figure 9 that a variety of coannihilation and annihilation scenarios are compatible with Yukawa unification and neutralino dark matter. Included in the m_A - $m_{\tilde{\chi}_1^0}$ plane is the line $m_A = 2m_{\tilde{\chi}_1^0}$ which indicates that the A funnel region is compatible with GYU. In the remaining planes in Figure 9, we draw the unit slope line which indicates the presence of gluino and stau coannihilation and bino-higgsino mixed dark matter scenarios.

Recent results from ATLAS [32, 33] and CMS [31] naively put very stringent limits on the gluino mass of $m_{\tilde{g}} \gtrsim 500$ GeV. However, it is shown explicitly in [34] that this limit does not apply in general, and specifically, does not apply in the case of heavy \gtrsim TeV squarks. In the gluino coannihilation channel shown in Figure 9 the squarks are heavy and are not yet excluded by ATLAS/CMS. The recent results do seem to suggest that the gluino coannihilation scenario will soon be tested.

7 Gauge-Yukawa unification and dark matter detection

In light of the recent results by the CDMS-II [35] and Xenon100 [36] experiments, it is important to see if GYU, within the framework presented in this paper, is testable from the perspective of direct and indirect detection experiments. The question of interest is whether $\mu \sim M_1$ is consistent with GYU, as this is the requirement to get a bino-higgsino admixture for the lightest neutralino which, in turn, enhances both the spin dependent and spin independent neutralino-nucleon scattering cross sections [37]. In Figure 10 we show the spin independent and spin dependent cross sections as a function of the neutralino mass. In the case of spin independent cross section, we also show the current experimental bounds and future reach of the CDMS and Xenon experiments. The color coding is the same as in Figure 9. A small region of the parameter space consistent with GYU and the experimental constraints discussed in Section 3 (red points in the figure) is at the exclusion limits set by the current CDMS and XENON experiments. Thus, the ongoing and planned direct detection

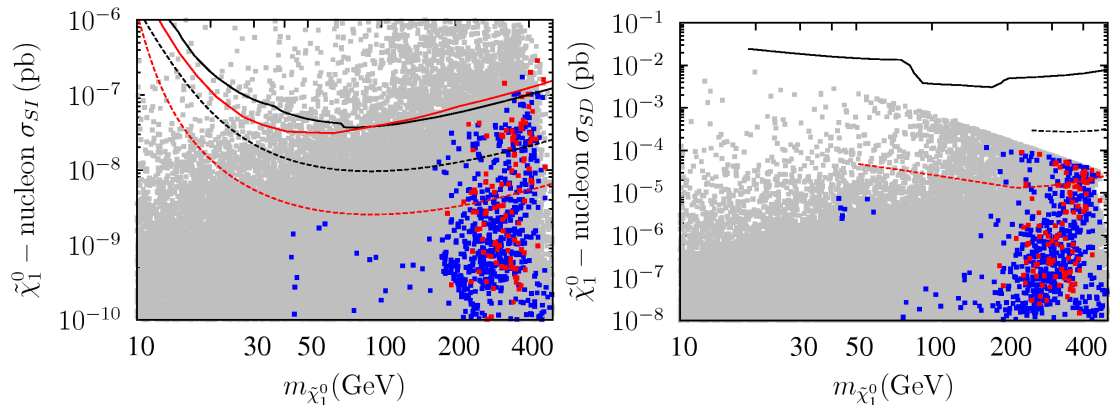


Figure 10: Plots in the $\sigma_{SI} - m_{\tilde{\chi}_1^0}$ and $\sigma_{SD} - m_{\tilde{\chi}_1^0}$ planes. Color coding is the same as in Figure 9. In the $\sigma_{SI} - m_{\tilde{\chi}_1^0}$ plane we show the current bounds (solid lines) and future reaches (dotted lines) of the CDMS (black lines) and Xenon (red lines) experiments. In the $\sigma_{SD} - m_{\tilde{\chi}_1^0}$ plane we show the current bounds from Super K (black line) and IceCube (dotted black line) and future reach of IceCube DeepCore (dotted red line).

experiments will play a vital role in testing GYU models.

In the case of spin dependent cross section, we show in Figure 10 the current bounds from the Super-K [38] and IceCube [39] experiments and the projected reach of IceCube DeepCore. The current Super-K and IceCube bounds are not stringent enough to rule out anything. However, from Figure 10 we see that the future IceCube DeepCore experiment will be able to constrain a significant region of the parameter space.

In Table 1 we present some benchmark points for the 4-2-2 GYU model. All of these points are consistent with neutralino dark matter and the constraints mentioned in Section 3. Point 1 represents the best GYU that we have found and corresponds to the A funnel region. Points 2 and 3 correspond to the gluino and stau coannihilation channels, while for Point 4 bino-Higgsino mixing plays a major role in giving the correct dark matter relic density. As expected, both the spin independent and spin dependent cross sections of the neutralinos on protons are larger for Point 4. Note that Point 3 also satisfies the lower bound on $\Delta(g-2)_\mu$. Finally, point 5 represents the best GYU solution that we found in the case of same sign gauginos ($GY \simeq 1.14$). All of the points shown in this Table are currently allowed by ATLAS/CMS [34].

8 Conclusions

Guage-Yukawa unification (GYU) at M_{GUT} , a natural extension of four dimensional gauge unification, is implemented using higher dimensional theories in which the

| | Point 1 | Point 2 | Point 3 | Point 4 | Point 5 |
|------------------------------|----------------------|-----------------------|-----------------------|----------------------|-----------------------|
| m_0 | 2063 | 3246 | 729 | 1769 | 7171 |
| M_1 | 747 | 1034 | -418 | 985 | 583 |
| M_2 | 1742 | 1819 | -1455 | 1938 | 939 |
| M_3 | -744 | -143 | 1138 | -443 | 49 |
| $\tan \beta$ | 50 | 48 | 47 | 50 | 53 |
| A_0/m_0 | -1.73 | 1.94 | -0.19 | -0.61 | -2.53 |
| m_{Hu} | 2191 | 1162 | 657 | 1328 | 4557 |
| m_{Hd} | 2797 | 3286 | 1294 | 2330 | 6722 |
| m_t | 174.3 | 174.1 | 174.2 | 174.4 | 173.1 |
| $\text{sgn } \mu$ | +1 | +1 | -1 | +1 | +1 |
| m_h | 117 | 119 | 119 | 116 | 121 |
| m_H | 597 | 1739 | 694 | 1102 | 987 |
| m_A | 594 | 1728 | 689 | 1095 | 983 |
| m_{H^\pm} | 605 | 1742 | 701 | 1106 | 993 |
| $m_{\tilde{\chi}_{1,2}^0}$ | 340, 528 | 459, 1530 | 193, 1040 | 428, 492 | 296, 907 |
| $m_{\tilde{\chi}_{3,4}^0}$ | 529, 1492 | 2708, 2710 | 1058, 1256 | 503, 1629 | 6694, 6694 |
| $m_{\tilde{\chi}_{1,2}^\pm}$ | 534, 1478 | 1531, 2709 | 1050, 1247 | 497, 1618 | 909, 6686 |
| $m_{\tilde{g}}$ | 1750 | 516 | 2503 | 1128 | 340 |
| $m_{\tilde{u}_{L,R}}$ | 2732, 2485 | 3445, 3209 | 2451, 2260 | 2319, 1946 | 7186, 7110 |
| $m_{\tilde{t}_{1,2}}$ | 1355, 1793 | 1788, 2091 | 1846, 2091 | 1153, 1643 | 1948, 2607 |
| $m_{\tilde{d}_{L,R}}$ | 2733, 2511 | 3445, 3276 | 2452, 2272 | 2321, 1982 | 7186, 7195 |
| $m_{\tilde{b}_{1,2}}$ | 1336, 1781 | 1485, 2065 | 1801, 2074 | 924, 1635 | 2407, 2852 |
| $m_{\tilde{\nu}_1}$ | 2335 | 3412 | 1177 | 2148 | 7161 |
| $m_{\tilde{\nu}_3}$ | 1841 | 2814 | 1048 | 1835 | 5218 |
| $m_{\tilde{e}_{L,R}}$ | 2336, 2115 | 3412, 3335 | 1181, 784 | 2149, 1854 | 7160, 7251 |
| $m_{\tilde{\tau}_{1,2}}$ | 540, 1836 | 1911, 2815 | 202, 1059 | 947, 1833 | 2129, 5204 |
| $\sigma_{SI}(\text{pb})$ | 9.1×10^{-9} | 4.7×10^{-12} | 2.7×10^{-10} | 2.5×10^{-8} | 1.1×10^{-12} |
| $\sigma_{SD}(\text{pb})$ | 5.6×10^{-6} | 5.4×10^{-10} | 9.0×10^{-8} | 3.4×10^{-5} | 7.8×10^{-12} |
| $\Omega_{CDM} h^2$ | 0.09 | 0.1 | 0.11 | 0.08 | 0.10 |
| R | 1.05 | 1.07 | 1.08 | 1.04 | 1.13 |
| GY | 1.05 | 1.09 | 1.09 | 1.06 | 1.14 |

Table 1: Point 1 is the best GYU we found corresponding to the A funnel region. Points 2 and 3 respectively correspond to the gluino and stau coannihilation channels, while for Point 4 the LSP is a bino-Higgsino admixture. Point 5 represents the best GYU solution we found with same sign gauginos and corresponds to gluino NLSP.

gauge and third (t - b - τ) family matter supermultiplets are unified. One of the simplest

realizations of this idea gives rise, after compactification, to the well-known symmetry group $SU(4)_c \times SU(2)_L \times SU(2)_R$. GYU in this framework strongly prefers gaugino masses M_2 and M_3 with opposite signs, and it also shows some preference for a top mass that is slightly higher than 173.3 GeV, its current central value. We have explored the fundamental parameter space of GYU models and identify a number of benchmark points that are compatible with a large variety of experimental constraints, including the WMAP bound on neutralino dark matter and $(g-2)_\mu$. One of the more intriguing GYU compatible solutions corresponds to the gluino NLSP scenario which can be tested at the LHC.

Acknowledgments

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